

1

NON-PROVISIONAL PATENT APPLICATION

CROSS REFERENCE TO RELATED APPLICATIONS

5

This application is a divisional application of co-pending application Serial Number 10/072,587, filed February 8, 2002 and claims the benefit of U.S. Provisional Application number 60/267,306 filed on February 8, 2001. The subject matters of the prior applications are incorporated in their entirety herein by reference thereto.

FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with government support under Contract No. N00024-01-C-4034 awarded by the United States Navy.

10

TITLE

Current Control Device

BACKGROUND OF THE INVENTION

1. Field of the Invention

15 The present invention generally relates to a current control device for regulating current flow. The invention specifically described is a device wherein current flow is regulated by compression and expansion of a composite.

2. Related Arts

20 Mechanical circuit breakers are best described as a switch wherein a contact alters the electrical impedance between a source and a load. Mechanical breakers are typically composed of a snap-action bimetal-contact assembly, a mechanical latch/spring assembly, or an expansion wire. Such devices are neither gap-less nor shock resistant, therefore prone to chatter and subject to arcing. Chatter and arcing pose substantial

22

1 problems in many high-voltage applications.

2 Variably conductive composites are applicable to current control devices.
3 Compositions include positive temperature coefficient resistive (PTCR), polymer current
4 limiter (PCL), and piezoresistive formulations. PTCR and PCL applications and
5 compositions and piezoresistive compositions are described in the related arts.

6 Anthony, United States Patent No. 6,157,528, describes and claims a polymer
7 fuse composed of a PTCR composition exhibiting temperature-dependent resistivity
8 wherein low resistivity results below and high resistivity results above a transition
9 temperature.

10 PTCR composites are composed of a conductive filler within a polymer matrix
11 and an optional nonconductive filler. Chandler et al., United States Patent No. 5,378,407,
12 describes and claims a PTCR composite having a crystalline polymer matrix, a nickel
13 conductive filler, and a dehydrated metal-oxide nonconductive filler. Sadhir et al., United
14 States Patent No. 5,968,419, describes and claims a PTCR composite having an
15 amorphous polymer matrix, a thermoplastic nonconductive filler, and a conductive filler.
16 During a fault, the composite heats thereby increasing volumetrically until there is
17 sufficient separation between particles composing the conductive filler to interrupt current
18 flow. Thereafter, the composite cools and shrinks restoring conduction. This self-restoring
19 feature limits PTCR compositions to temporary interrupt devices.

20 PCL composites, like PTCR compositions, are a mixture of a conductive filler
21 and a polymer. However, PCL composites are conductive when compressed and interrupt
22 current flow by polymer decomposition. For example, Duggal et al., United States Patent

1 No. 5,614,881, describes a composite having a pyrolytic-polymer matrix and an
electrically conductive filler. During a fault, temperature within the composite increases
causing limited decomposition and evolution of gaseous products. Current flow is
interrupted when separation occurs between at least one electrode and conductive
5 polymer. Gap dependent interrupt promotes arcing and arc related transients.
Furthermore, static compression of the composites increases time-to-interrupt by damping
gap formation. Neither PTCR nor PCL applications provide for the dynamically-tunable
compression of a composite in response to electrical load conditions.

Piezoresistive composites, also referred to as pressure conduction
10 composites, exhibit pressure-sensitive resistivity rather than temperature or decomposition
dependence. Harden et al., United States Patent No. 4,028,276, describes piezoresistive
composites composed of an electrically conductive filler within a polymer matrix with an
optional additive. Conductive particles comprising the filler are dispersed and separated
within the matrix, as shown in Figures 1A and 1C. Consequently, piezoresistive
15 composites are inherently resistive becoming less resistive and more conductive when
compressed. Compression reduces the distance between conductive particles thereby
forming a conductive pathway, as shown in Figures 1B and 1D. The composite returns to
its resistive state after compressive forces are removed. However, piezoresistive
compositions resist compression.

20 Pressure-based interrupt facilitates a more rapid regulation of current flow as
compared to PTCR and PCL systems. Temperature dependent interrupt is slowed by the
22 poor thermal conduction properties of the polymer matrix. Decomposition dependent

1 interrupt is a two-step process requiring both gas evolution and physical separation
between electrode and composite. Furthermore, decomposition limits the life cycle of a
composition.

Active materials, including but not limited to piezoelectric, piezoceramic,
5 electrostrictive, magnetostrictive, and shape-memory alloy materials, are ideally suited for
the controlled compression of piezoresistive composites thereby achieving rapid and/or
precise changes to resistivity. Active materials facilitate rapid movement by mechanically
distorting or resonating when energized. High-bandwidth active materials are both
sufficiently robust to exert a large mechanical force and sufficiently precise to controllably
10 adjust force magnitude.

As a result, an object of the present invention is to provide a current control
device tunably and rapidly compressing a pressure-dependent conductive composite. A
further object of the present invention is to provide a device that eliminates arcing thereby
facilitating a complete current interrupt. It is an additional object of the present invention
15 to provide a device that quenches transient spikes associated with shut off.

SUMMARY OF THE INVENTION

The present invention is a current control device controlling current flow via
the tunable compression of a polymer-based composite in response to electrical load
conditions. The invention includes a pressure conduction composite compressed by at
20 least one pressure plate. In several embodiments, the composite is compressed by a
conductive pressure plate. In other embodiments, the composite is compressed by a
22 nonconductive pressure plate and current flow occurs between two electrodes contacting

1 the composite. The composite is variably-resistive and typically composed of a conductive
filler, examples including metals, metal-nitrides, metal-carbides, metal-borides, metal-
oxides, within a nonconductive matrix, examples including polymers and elastomers.
Optional additives typically include oil, preferably silicone-based.

5 A compression mechanism applies, varies, and removes a compressive force
acting on the composite. Compression mechanisms include electrically driven devices
comprised of actuators composed of an active material extending and/or contracting when
energized. Active materials include piezoelectric, piezoceramic, electrostrictive,
magnetostrictive and shape memory alloys. Piezo-controlled pneumatic devices are also
10 appropriate. Actuator movement adjusts the pressure state within the composite thereby
altering resistivity within the confined composite.

Several advantages are offered by the present invention. Compression-based
control of a pressure-sensitive conduction composite provides a nearly infinite life cycle. A
gap-less interrupt eliminates arcing and arc quenching requirements. The present invention
15 lowers fault current thereby avoiding stress related chatter. Parallel arrangements of the
present invention offer power handling equal to the sum of the individual units.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described in more detail, by way of example only,
with reference to the accompanying drawings, in which:

20 FIG. 1 is a schematic diagram showing exemplary microstructures for composites before
and after compression.

22 FIG. 2 is a flowchart of composite manufacturing method.

- 1 FIG. 3 is a side elevation view of a pressure switch with conductive pressure plates.
- FIG. 4 is a side elevation view of a pressure switch with nonconductive pressure plates.
- FIG. 5 is a side elevation view of a current controller comprised of four pressure switches wherein pressure plates are pushed by actuators.
- 5 FIG. 6 is a side elevation view of a current controller comprised of four pressure switches wherein pressure plates are pulled by actuators.
- FIG. 7 shows a parallel arrangement of current controllers comprising a single unit.
- FIG. 8 is a top elevation view of pressure switch showing cylindrical pores oriented through electrodes.
- 10 FIG. 9 is a section view of pressure switch showing cylindrical holes through switch thickness.
- FIG. 10 is a section view of pressure switch showing cylindrical holes within composite.
- FIG. 11 is a section view of pressure switch showing cylindrical holes filled with a temperature sensitive material.
- 15 FIG. 12 is a side elevation view of temperature activated switch.
- FIG. 13 is a side elevation view of temperature activated switch.

REFERENCE NUMERALS

- 1 Current controller
- 2 Conductive filler
- 20 3 Nonconductive matrix
- 4 Composite
- 22 6 First electrode

- 1 7 Second electrode
- 11 Pressure switch
- 18 Pressure plate
- 19 Actuator
- 5 22 Force
- 30 Restoration element
- 31 Conductor
- 32 Insulator
- 33 Insulator
- 10 40 Hole
- 41 Temperature sensitive material
- 51 Temperature sensitive actuator
- 52 Wire
- 53 Wire
- 15 54 Nonconducting terminal
- 55 Rigid element
- 56 Thermal element

DESCRIPTION OF THE INVENTION

Two embodiments of the present invention are comprised of a rectangular

20 solid composite 4 contacting and sandwiched between two or more plates, namely a planar

first electrode 6 and a planar second electrode 7, as shown in FIG. 3, and a planar first

22 electrode 6 and a planar second electrode 7 and two planar pressure plates 18a, 18b, as

1 shown in FIG. 4. A pressure switch 11 is comprised of a composite 4 and electrodes 6, 7
as shown in FIG. 3 or a composite 4 and pressure plates 18a, 18b as shown in FIG. 4.

The composite 4 functionally completes the current path between first
electrode 6 and second electrode 7 during acceptable operating conditions and interrupts
5 current flow when a fault condition occurs. The composite 4 is either conductive or
resistive based on the pressure state within the composite 4. For example, the composite 4
may be conductive above and nonconductive below a threshold pressure. Alternately, the
resistivity of the composite 4 may vary with pressure over a range of resistance values.

A typical composite 4 is a pressure dependent conductive material, for
10 example a piezoresistive formulation, comprised of a nonconductive matrix 3 and a
conductive filler 2, as schematically shown in FIG. 1. Preferred mixtures have a volume
fraction below the percolation threshold wherein conductive filler 2 is randomly dispersed
within the nonconductive matrix 3. During compression, the nonconductive matrix 3
between conductive filler 2 particles is dimensionally reduced thereby crossing the
15 percolation threshold.

The nonconductive matrix 3 is a resistive, yet compressible material including
but not limited to polymers and elastomers. Specific examples include polyethylene,
polystyrene, polyvinylidene fluoride, polyimide, epoxy, polytetrafluorethylene, silicon rubber,
polyvinylchloride, and combinations thereof. Preferred embodiments are comprised of the
20 elastomer RTV R3145 manufactured by the Dow Corning Company.

The conductive filler 2 is an electrically conductive material including but not
22 limited to metals, metal-based oxides, nitrides, carbides, and borides, and carbon black.

1 Preferred fillers resist deformation under compressive loads and have a melt temperature
sufficiently above the thermal conditions generated during current interrupt. Specific metal
examples include aluminum, gold, silver, nickel, copper, platinum, tungsten, tantalum,
iron, molybdenum, hafnium, combinations and alloys thereof. Other example fillers include
5 Sr(Fe,Mo)O_3 , (La,Ca)MnO_3 , Ba(Pb,Bi)O_3 , vanadium oxide, antimony doped tin oxide,
iron oxide, titanium diboride, titanium carbide, titanium nitride, tungsten carbide, and
zirconium diboride.

FIG. 2 describes a fabrication method for various composites 4. Generally,
composites 4 are prepared from high-purity feedstock, mixed, formed into a solid, and
10 suffused with oil. One or more plates are adhered to the composite 4.

Feedstocks include both powders and liquids. Conductive filler 2 feedstock is
typically composed of a fine, uniform powder, one example being 325 mesh titanium
carbide. Nonconductive matrix 3 feedstock may include either a fine, uniform powder or a
liquid with sufficiently low-viscosity to achieve adequate dispersion of powder. Powder-
15 based formulations are mechanically mixed and compression molded using conventional
methods. Polytetrafluorethylene formulations may require sintering within an oven to
achieve a structurally durable solid. Powder-liquid formulations, one example being
titanium carbide and a silicone-based elastomer, are vulcanized and hardened within a die
under low uniaxial loading at room temperature.

20 The solid composite 4 is placed within a liquid bath thereby allowing
infiltration of the additive into the solid. Additives are typically inorganic oils, preferably
silicone-based. The composite 4 is exposed to the additive bath to insure complete
22

1 suffusion of the solid, whereby exposure time is determined by dimensions and
composition of the composite 4. For example, a 0.125-inch by 0.200-inch by 0.940-inch
composite 4 composed of titanium carbide having a volume fraction of 66 percent and
RTV R3145 having a volume fraction of 34 percent was suffused over a 48 hour period.

5 Conductive or nonconductive plates are adhered to the composite 4 either
before or after suffusion. If prior to suffusion, plates are placed within the die along with
the liquid state composite 4. For example, a silicone elastomer composite 4 is adequately
bonded to two 0.020-inch thick brass plates by curing at room temperature typically
between 3 to 24 hours or at an elevated temperature between 60 to 120 degrees Celcius
10 for 2 to 10 hours. If after suffusion, silicone adhesive is applied between plate and
composite 4 and thereafter mechanically pressed to allow for proper bond formation.

A porous, nonconductive matrix 3 improves compression and cooling
characteristics of the composite 4 without degrading electrical properties. A porous
structure is formed by mechanical methods, one example including drilling, after
15 fabrication of the solid composite 4. Another method includes the introduction of pores
during mixing of a powder-based conductive filler 2 with a liquid-based nonconductive
matrix 3. An additional method includes the introduction of pores during compression
forming the composite 4. Also, pores are formed by heating the composite 4 within an
oven resulting in localized heating or phase transitions that result in void formation and
20 growth. Furthermore, highly compressible microspheres composed of a low-density, high-
temperature foam may be introduced during mixing. Pores are either randomly oriented or
22 arranged in a repeating pattern. Pore shapes include but are not limited to spheres,

1 cylinders, and various irregular shapes. A single pore may completely traverse the thickness of a composite 4.

FIGS. 8-9 show an embodiment wherein a plurality of holes 40 traverse the cross section of a pressure switch 11. FIG. 10 shows an embodiment wherein holes
5 traverse the composite 4 within the pressure switch 11.

FIG. 11 shows a further embodiment wherein holes 40 are filled with a temperature sensitive material 41, examples including rods or springs composed of a shape memory alloy. Functionally, the temperature sensitive material 41 is typically a rubbery material below, see FIG. 11a, and hard above, see FIG. 11b, a phase transition
10 temperature. More importantly, the temperature sensitive material 41 produces a large force above a transition temperature designed within the material as readily understood within the art. This force is sufficiently capable of moving the pressure plates 18 or electrodes 6,7 apart and interrupting current flow. The temperature sensitive material 41 is self restoring thereby facilitating current flow after the surrounding composite 4 has
15 cooled.

FIGS. 12-13 show two embodiments wherein at least two temperature sensitive actuators 51 apply a compressive force 22 onto a composite 4 thereby allowing current flow. In FIG. 12, current flows directly through the temperature sensitive actuators 51a, 51b, preferably a shaped memory alloy. When a fault occurs the
20 temperature sensitive actuators 51a, 51b are heated and contract thereby decompressing the composite 4 and interrupting current. The composite 4 is compressed as the temperature sensitive actuator 51 cools. In FIG. 13, current flows through the first
22

1 electrode 6 and the second electrode 7 when temperature sensitive actuators 51a, 51b are
heated by thermal elements 56a, 56b. Thermal elements 56a, 56b are deactivated when a
fault condition occurs thereby decreasing the length of the temperature sensitive actuators
51a, 51b and reactivated after the fault condition is corrected thereby increasing the length
5 of the temperature sensitive actuators 51a, 51b causing compression of the composite 4
and current flow.

FIGS. 5-6 show additional embodiments of the present invention comprised of
four pressure switches 11a, 11b, 11c, 11d, a first electrode 6, a second electrode 7, two
planar conductors 31a, 31b, four insulators 32a, 32b, 33a, 33b, a restoration element 30,
10 and a pair of actuators 19a, 19b.

Pressure switches 11a, 11b, 11c, 11d are composed of a pressure conduction
composite 4 disposed between and adhered to two electrically conducting plates, as
described above. A pair of pressure switches 11 are electrically aligned in a serial
arrangement about a single electrode, either the first electrode 6 or the second electrode 7.
15 One electrically conducting plate from each pressure switch 11 directly contacts the
electrode. Two such pressure switch 11 and electrode arrangements are thereafter aligned
parallel and disposed between, perpendicular to and contacting a pair of conductors 31a,
31b so that each pressure switch 11 in a serial arrangement contacts a separate conductor
31. Conductors 31 are composed of materials known within the art and should have
20 sufficient strength to resist deformation when a mechanical load is applied. Thereafter, an
insulator 32 is placed in contact with and attached or fixed to each conductor 31. A typical
22 insulator 32 is a planar element composed of an electrically nonconducting material with

1 sufficient strength to resist deformation when a mechanical load is applied.

At least one restoration element 30 is disposed between and parallel to the serial arrangement of pressure switches 11 and electrodes 6 or 7. The restoration element 30 is attached to separate electrically nonconductive insulators 33a, 33b. Thereafter, insulators 33a, 33b are mechanically attached to, perpendicularly disposed and between the conductors 31a, 31b. Insulators 33a, 33b electrically isolate the restoration element 30 from conductors 31a, 31b. The restoration element 30 decompresses the composite 4 within each pressure switch 11, returning it to its original thickness, when the compressive mechanical load is removed from the insulators 32a, 32b. A restoration element 30 may be a mechanical spring or coil, a pneumatic device, or any similar device that provides both extension and contraction.

In preferred embodiments, an actuator 19 contacts an insulator 32. In one embodiment, at least one actuator 19 is attached or fixed to each insulator 32 opposite of said conductor 31, as shown in FIG. 5. A pair of actively opposed yet equal actuators 19a, 19b apply a mechanical load by pushing onto electrically nonconductive insulators 32a, 32b to compress the composite 4 within each pressure switch 11a, 11b, 11c, 11d, as shown in FIG. 5b. In another embodiment, at least two actuators 19a, 19b are mechanically attached or fixed to a pair of insulators 32a, 32b, see FIG. 6. Again, a pair of actively opposed yet equal actuators 19a, 19b apply a mechanical load by pulling on electrically nonconductive insulators 32a, 32b to compress the composite 4 within each pressure switch 11a, 11b, 11c, 11d, as shown in FIG. 6b.

22 Variations to the described embodiments also include at least two or more

1 actively opposed actuators 19 mechanically compressing one or more current controllers
1. FIG. 7 describes a three-by-three arrangement of nine current controllers 1, however
not limited to this arrangement. In such embodiments, current controllers 1 are electrically
connected parallel thereby providing a total power handling capability equal to the sum of
5 the power handling of individual units.

One or more actuators 19 may be employed to drive two or more current
controllers 1. For example, a single actuator 19 or two actively opposed yet equal
actuators 19 may apply a mechanically compressive load onto the current controllers 1 so
that all are simultaneously compressed and decompressed. Alternatively, one or a pair of
10 actuators 19 may apply a mechanically compressive load onto each individual current
controller 1. In this embodiment, it is possible to simultaneously drive all current
controllers 1 or to selectively drive a number of units.

The embodiments described above may also include a current measuring
device electrically coupled before or after the current controller 1. This device provides
15 real-time sampling of current conditions which are thereafter communicated to the
actuators 19. Such monitoring devices are known within the art.

An actuator 19 is a rigid beam-like element composed of an active material
capable of dimensional variations when electrically activated. For example, the actuator 19
may extend, contract, or extend and contract, as schematically represented by arrows in
20 FIGS. 5-6. Extension of the actuator 19 increases the overall length of the actuator 19.
Actuators 19 are composed of electrically activated devices including piezoelectric,
22 piezoceramic, electrostrictive, magnetostrictive, and shape memory alloy materials. For

1 example, piezoelectric and piezoceramic materials may be arranged in a planar stack along
the actuator 19. Shape memory alloys are mechanically distorted by heating via electrical
conduction or heat conduction from an adjacent body, one example including the
composite 4 during fault condition. Alternatively, an actuator 19 may be a commercially
5 available high-speed piezo-controlled pneumatic element comprised of a pneumatic
diaphragm with pilot operated high-bypass valve.

The description above indicates that a great degree of flexibility is offered in
terms of the present invention. Although embodiments have been described in considerable
detail with reference to certain preferred versions thereof, other versions are possible.
10 Therefore, the spirit and scope of the appended claims should not be limited to the
description of the preferred versions contained herein.

15

20

22